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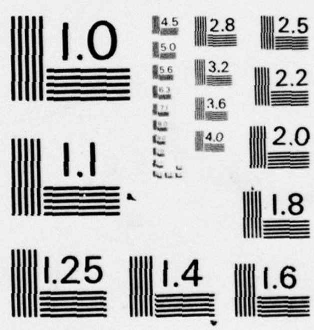

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ANNUAL REPORT

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GRANT AFOSR 74-2703A

JULY 30, 1976

A. J. MCEVILY

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ANNUAL REPORT

FATIGUE CRACK PROPAGATION IN TITANIUM ALLOYS

GRANT AFOSR 74-2703A

JULY 30, 1976

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ANNUAL REPORT

Introduction

This report reviews the research accomplished on the fatigue of Ti-6Al-4V forgings and related matters during the period 1 July 1975 to 30 June 1976. This research has involved studies of fatigue crack initiation as well as fatigue crack propagation. Principal findings have been that subsurface fatigue cracks can be initiated in forgings of this titanium alloy when the α-phase size is of the order of 10μ, a size which can be present in large forgings. This mode of fatigue crack initiation can have a deleterious effect on long-life fatigue performance at positive mean stress levels. Results of the fatigue crack propagation studies have shown that the rate of fatigue crack growth in air and in vacuum can be analyzed in terms of a modified continuum mechanics treatment of fatigue crack growth based upon the concept that the fatigue crack growth increment per cycle is related to the extent of crack opening displacement. Further details concerning each of these related research areas are given below.

Fatigue Crack Initiation

This study of the fatigue initiation process in Ti-6Al-4V forgings has involved the fatigue testing of polished specimens which have been subjected to different types of heat treatments in order to vary the microstructural characteristics. Fatigue testing has been carried out under axial loading with mean stress or R-ratio the principal variable. Particular attention has been focused on the high life (up to 10^8 cycles) fatigue behavior in order to understand why the fatigue behavior of heavy forgings (coarse microstructure) is poor relative to bar stock (fine microstructure) for

R=0 loading. Our findings indicate that under load control the alloy cyclically softens which means that the amount of plastic deformation per cycle increases during testing. Further, because of the nature of the slip process in this alloy, high internal stresses develop as evidenced by a pronounced Bauschinger effect as compared to materials such as steel or aluminum alloys. These internal stress fields are highly localized at the low stress amplitudes which correspond to the high-life region of the S-N curve, and apparently these stresses are sufficiently high to nucleate sub-surface cracks along the $\{10\bar{1}7\}$ planes in the hcp-α phase. Our present view is that such cracks are nucleated quite early in life by slip along prism planes in the α-phase. Growth of the cracks is controlled by the tensile stress range, and on this basis it is expected that the stress amplitude for R=0 loading for 10^8 cycles to failure would be about one-half that for R=-1 loading, and this view is consistent with the experimental data. A portion of this aspect of the research program has been written up and is covered in two publications which are:

1. R. K. Steele and A. J. McEvily, "The High-Cycle Fatigue Behavior of Ti-6Al-4V Alloy," Eng. Frac. Mechanics, 8, 31, 1976.
2. R. K. Steele and A. J. McEvily, "Effect of Mean Stress on Fatigue Behavior of Ti-6Al-4V Alloy," presented at the Third International Conference on Titanium, Moscow, May 1976, to be published.

Current studies which relate to this study include a detailed fractographic examination of the failed specimens to learn more of the conditions involved in crack initiation. Also transmission electron microscopy is being used to learn more of the cyclic-plastic deformation process with this alloy and hopefully relate these observations to the observed fatigue behavior. In addition we are preparing a paper on the effects of heat treatment on the fatigue behavior of Ti-6Al-4V.

Fatigue Crack Propagation

The study of the fatigue crack growth behavior of specimens from pancake forgings of Ti-6Al-4V has continued. The principal effort has been directed at the obtaining of rate of crack growth versus the range of the stress intensity factor over a wide range of crack growth rates in air and in vacuum (10^{-5} Pa) as a function of R level. The data obtained are of direct interest, but also provide an opportunity to compare with crack growth behavior expected on the basis of our analysis based upon crack-opening displacement considerations. Fig. 1 indicates the nature of the test results and the excellent agreement with the expected form of the crack growth curve. An unexpected finding in comparing air vs vacuum growth rates is that the vacuum environment has a beneficial effect even to the highest growth rates studied, and in fact may even affect the level of the fracture toughness, K_c. A particularly strong effect of the environment is noted in the threshold region where the threshold stress intensity range at R=0 is 6 ksi$\sqrt{in}$ in air as compared to 12 ksi$\sqrt{in}$ in vacuum. Similarly at R=0.8 the threshold stress intensity range is 2 ksi$\sqrt{in}$ in air as compared to 6 ksi$\sqrt{in}$ in vacuum. Based upon equal crack opening displacements in a given environment, the following expression can be used to calculate the magnitude of the stress intensity range, ΔK_{TH_R}, at any R value.

$$\Delta K_{TH_R} = \sqrt{\frac{1-R}{1+R}}\,\Delta K_{TH_o} \qquad (1)$$

where ΔK_{TH_o} is the threshold value for R=0 loading.

This expression agrees fairly well with our experimental results and can be used to estimate threshold stress-intensity ranges for R-values of interest if the range is known for one condition.

The following analytical expression has been used to compare with the crack growth data.

$$\frac{\Delta a}{\Delta N} = \frac{A}{\sigma_y E} (\Delta K - \Delta K_{TH_R})^2 \left(1 + \frac{\Delta K}{K_c - K_{max}}\right) \tag{2}$$

where $K_{max} = \frac{\Delta K}{1-R}$; A is a constant, a function of the environment; σ_y is the yield strength, and E is Young's modulus. This expression is slightly different from one used heretofore in that a $(\Delta K^2 - \Delta K_{TH}^2)$ factor has been replaced by a $(\Delta K - \Delta K_{TH})^2$ factor. This modification does not change the basic approach involved in the analysis. It was made to provide a better agreement between predicted and experimental results in the near threshold region. Until recently good data in the threshold region was not available to allow a determination of the best form for this factor, but it now appears that an effective stress intensity factor, $\Delta K - \Delta K_{TH}$, is more appropriate than an effective crack-opening displacement, $\Delta K^2 - \Delta K_{TH}^2$ in analyzing the data.

Table I provides an indication of the variation in the constants of Eq. 2. (Growth rate in units of inches/cycle).

Figure 1-5 indicate the nature of agreement between experimental and calculated results. Over the range from the threshold level to the fracture toughness level the agreement is quite good. Note that the influence of mean stress level is also well accounted for in the case of the data for the titanium alloy. A current consideration is the role of crack closure in this approach.

TABLE I

Material	σ_y, ksi	E, ksi	A	ΔK_{TH_o} ksi$\sqrt{in}$	K_c ksi$\sqrt{in}$
Titanium Alloys					
Ti-6Al-4V Forging in Air	120	17×10^3	.05	6	65
Ti-6Al-4V Forging in Vacuum	120	17×10^3	.02	12	80
Ti-6Al-4V Sheet in Air	140	17×10^3	.08	5	100
Aluminum Alloys					
2024-T3	57	10.8×10^3	.03	5	100
L64	52	10.6×10^3	.18	6	60
RR58	60	10.7×10^3	.04	4	21-24
Steels					
A514-B	129	30×10^3	.02	8	200
X65	65	30×10^3	.02	5	>150
En30a Unembrittled	107	30×10^3	.026	7	>200
En30a Embrittled	107	30×10^3	.026	7	50
Stainless Steel					
316L	41	30×10^6	.01	8	90

$$\frac{\Delta a}{\Delta N} = \frac{A}{\sigma_y E}\left(\Delta K - \Delta K_{TH_{(R)}}\right)^2 \left(1 + \frac{\Delta K}{K_c - K_{max}}\right)$$

$$K_{max} = \frac{\Delta K}{1-R}$$

$$\Delta K_{TH_{(R)}} = \sqrt{\frac{1-R}{1+R}}\,\Delta K_{TH_{(o)}}$$

$$\left(\text{In Inert Envir., } A \simeq \frac{\sigma_y}{E}\right)$$

Results of this phase of the study have been reported in two publications:

1. R. Ebara, K. Inoue, S. Crosby, J. Groeger and A. J. McEvily, "On Environmental Effects in Fatigue," to be presented at the Second International Conference on Materials, Boston, Aug. 1976.

2. A. J. McEvily and J. Groeger, "On the Threshold Level for Fatigue Crack Growth," submitted for presentation at the Fourth International Conference on Fracture, Waterloo, Canada, June 1977.

In addition A. J. McEvily participated in the ARPA Materials Research Council Session on Fatigue Crack Propagation in La Jolla, California, during the period 7-9 July 1976. He will also present the invited keynote lecture at a meeting on Fatigue at Cambridge University, 28-30 March 1977. Both of these occasions present the opportunity to present the results of our AFOSR program on fatigue of titanium alloys.

Current research on fatigue crack propagation is concerned with two areas. The first of these is the effect of an overload on subsequent crack growth. One aspect of the study is to determine the extent of the increase in the threshold level after an overload. If this change can be expressed as a function of overload it may be possible to provide a modification to Eq. (2) to include overload effects. The other main area of interest is the role of small defects on fatigue crack growth. Here some work of the principal investigator carried out some time back on non-propagating fatigue cracks may provide an approach. Consider that a fatigue crack is a stress raiser of notch stress concentration factor K_N where K_N is the Neuber stress concentration factor which is related to the theoretical stress concentration factor K_T by

$$K_N = 1 + \frac{K + -1}{1 + \sqrt{\rho'/\rho_e}} \tag{3}$$

where ρ_e is the effective value of a fatigue crack (a number usually of the order of 0.001 inch) and ρ' is the Neuber material constant introduced by him to account for the notch size effect. The local stress within a volume of material of depth ρ' is given as the product of Kn and the applied stress. If one postulates that cracks cannot grow until this load stress exceeds the endurance limit one can write the condition for the threshold to be

$$K_N \, \sigma_{NET} = \sigma_{end} \tag{4}$$

Now the stress intensity factor K can be defined as

$$K = \lim_{\rho \to o} K_T \, \sigma_{NET} \sqrt{\frac{\pi\rho}{4}} \tag{5}$$

If we replace K_T by K_N and let $\rho \to \rho_e$ instead of zero, we obtain

$$K = \underset{\rho \to \rho_e}{K_N} \, \sigma_{NET} \sqrt{\frac{\pi\rho_e}{4}} \tag{6}$$

In particular, at threshold

$$\Delta K_{TH} = K_N \Delta\sigma_{NET} \sqrt{\frac{\pi\rho_e}{4}} \tag{7}$$

Substituting Eq. (4) in Eq. (7) we obtain

$$\Delta K_{TH} = \sigma_{end} \sqrt{\frac{\pi\rho_e}{4}} \tag{8}$$

Since ΔK_{TH} is of the form $B\sigma\sqrt{a}$

$$B\Delta\sigma\sqrt{a} = \sigma_{end} \sqrt{\frac{\pi\rho_e}{4}} \tag{9}$$

or

$$\Delta\sigma = \frac{1^{\sigma}\text{end}}{B}\sqrt{\frac{\pi}{4}} \cdot \sqrt{\frac{\rho_e}{a}} \tag{10}$$

Eq. (10) suggests that when a, the defect size is equal to ρ_e or smaller that crack growth in stress controlled, that is

$$\Delta\sigma = \frac{1}{B}\sqrt{\frac{\pi}{4}}\ \sigma_{end} \tag{11}$$

However when a >> ρ_e then crack growth is controlled by the stress-intensity factor, K.

We will be carrying out a test program to establish the initiations of the fracture mechanics approach as well as to attempt to provide some insight into the physical significance of the Neuber constant, ρ_e. Participating in this study will be two graduate students, one post-doctoral research fellow, a research technician, as well as the principal investigator.

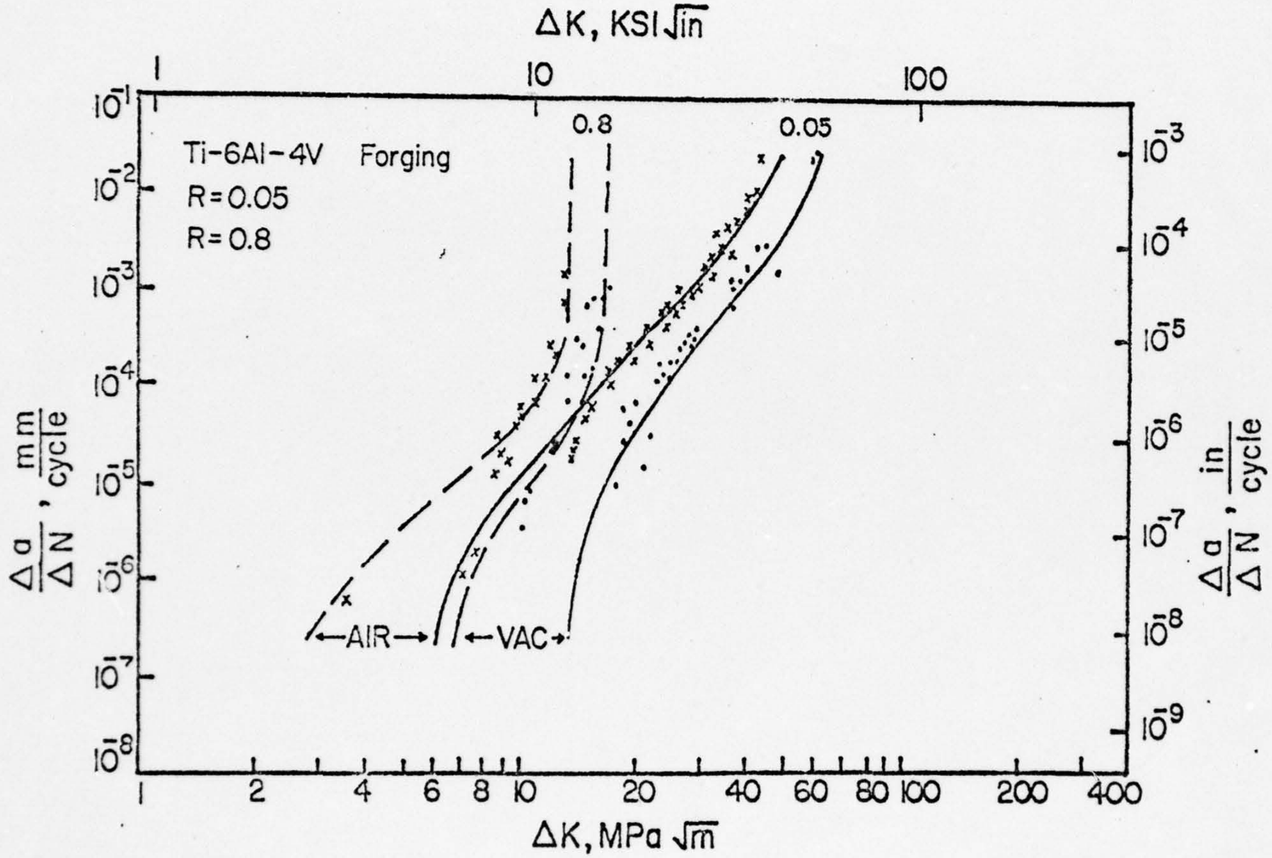

Fig. 1. Comparison of experimental and calculated crack propagation rates for Ti-6Al-4V forging. Present data.

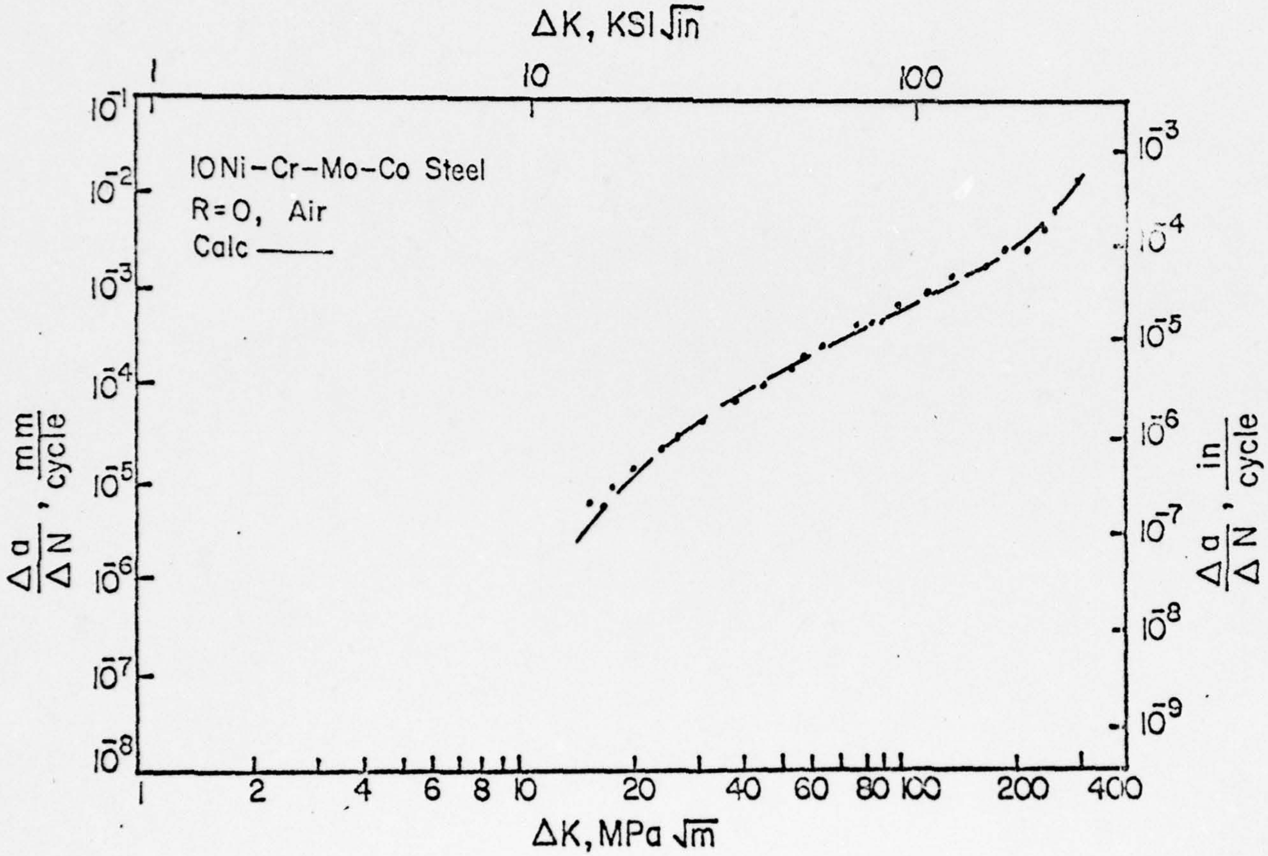

Fig. 2. Comparison of experimental and calculated crack propagation rates for a 10 Ni-Cr-Mo-Co steel. (Data of J. M. Barsom, E. J. Imhof and S. T. Rolfe, U.S Steel).

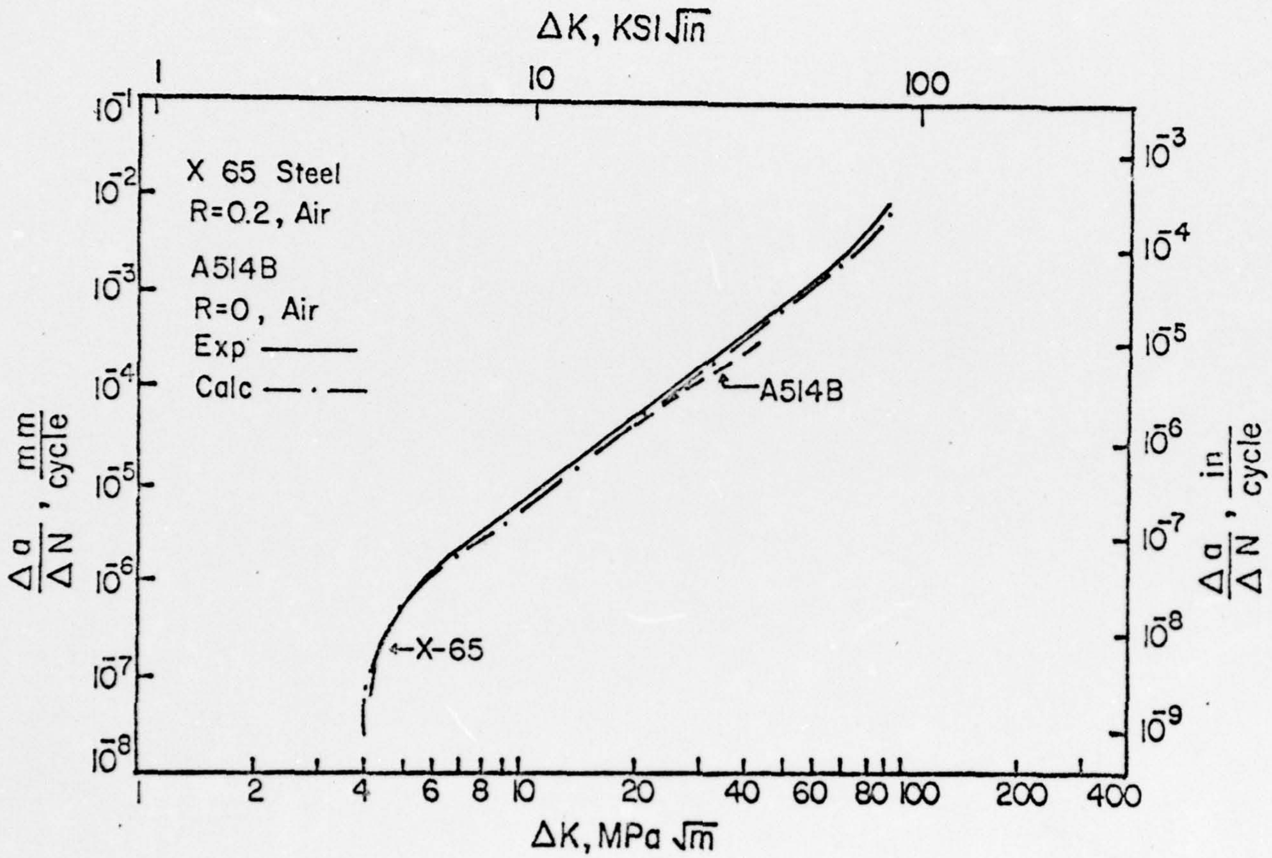

Fig. 3. Comparison of experimental and calculated crack propagation rates for X 65, data of O. Vosikowsky, J. Eng. Mat. and Tech., Oct. 1975; A-514B, data of J. M. Barsom, ASTM STP 536, 1973, 147.

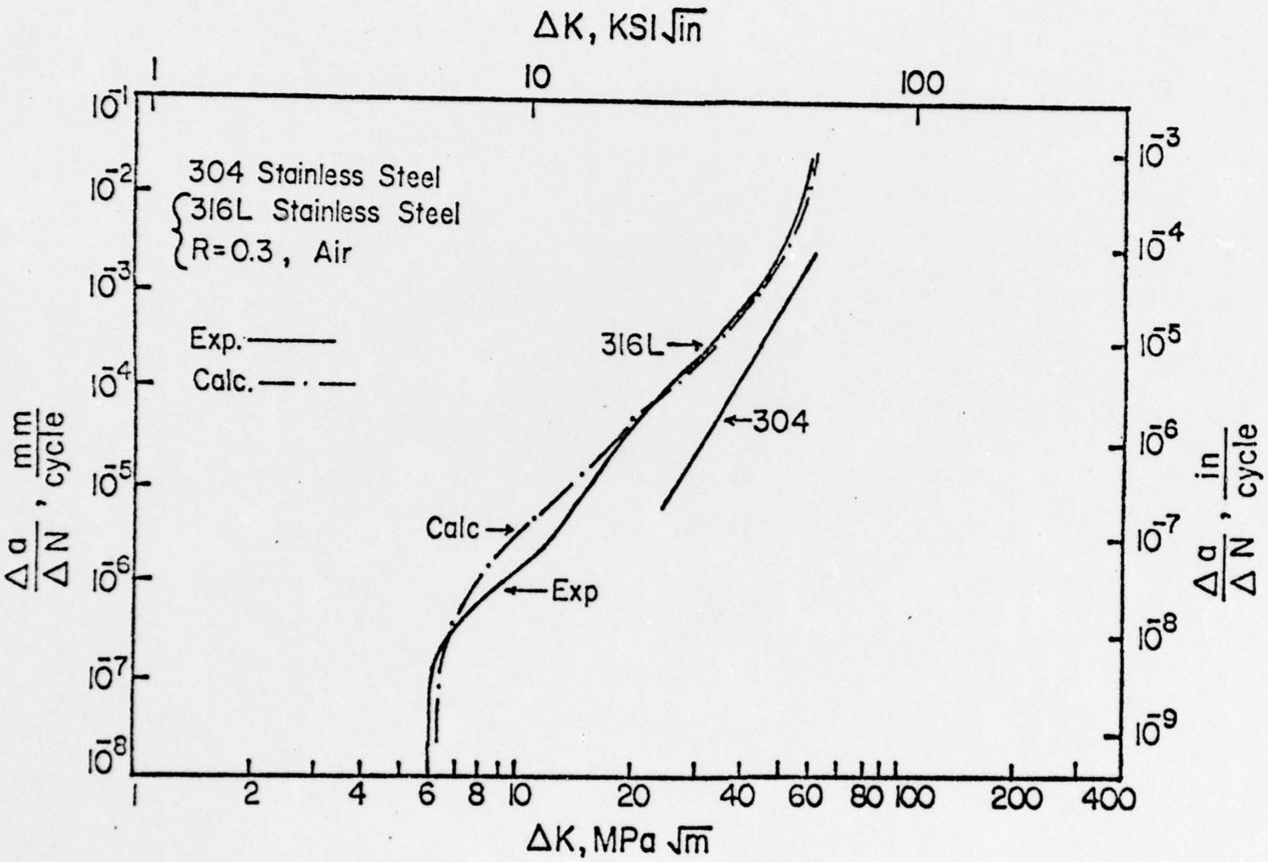

Fig. 4. Comparison of experimental and calculated crack propagation rates for 316L stainless steel, data of A. C. Picard, R. O. Ritchie, and J. F. Knott, Metals Technology, June 1975, 253; 304 stainless steel, data of C. Bathias and R. M. Pelloux, Met. Trans. 4, 1973, 1265 (R=0).

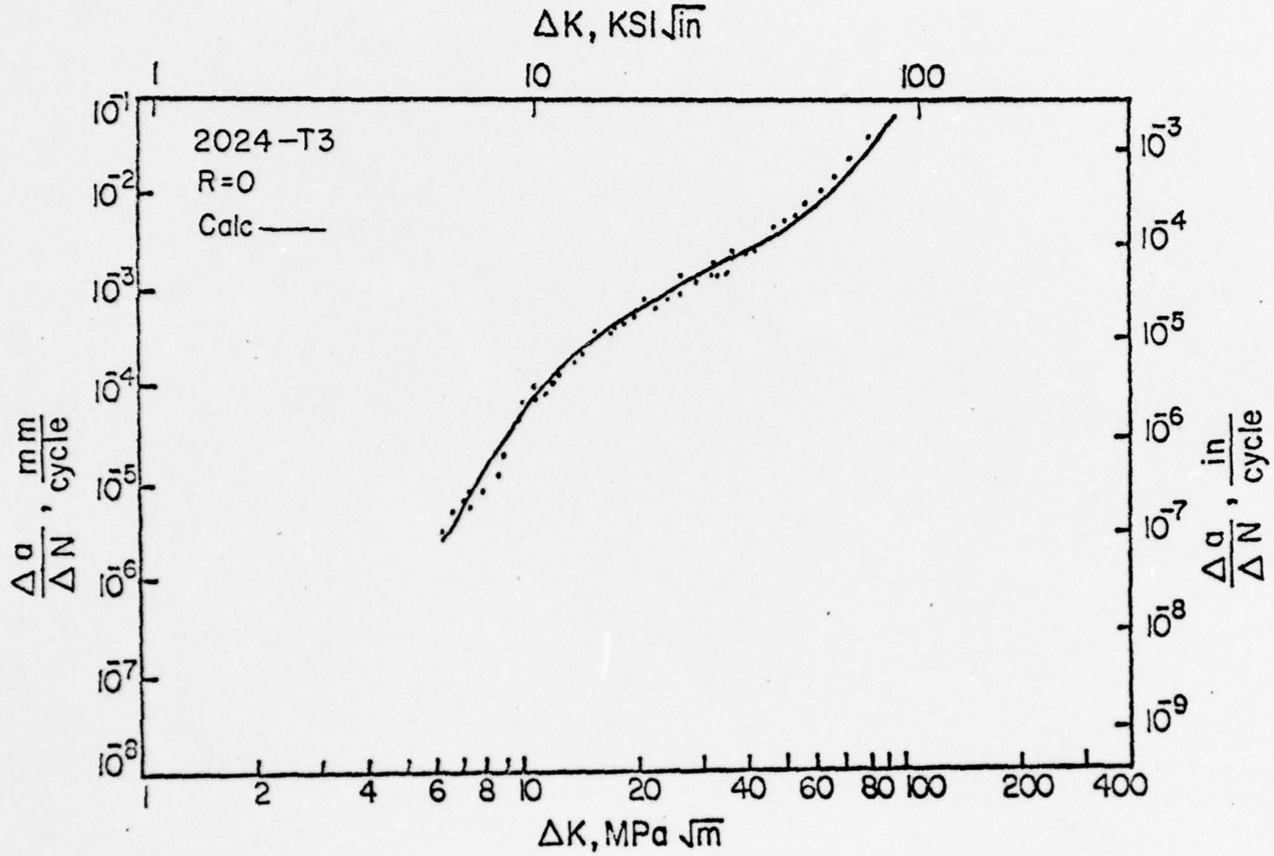

Fig. 5. Comparison of experimental and calculated crack propagation rates for 2024-T3 aluminum alloy. Data of A. J. McEvily and W. Illg, NACA TN 4394, 1958.

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